AD-682 129

D1-82-0806

BOEING SCIENTIFIC RESEARCH LABORATORIES

Flight Sciences Laboratory

DRIVER GAS CONTAMINATION IN SHOCK TUNNELS

by

J. Kenneth Richmond

R. J. Parsons

December 1968

Driver Gas Contamination in Shock Tunnels

by

J. Kenneth Richmond, Staff Member
Boeing Scientific Research Laboratories, Seattle, Washington

R. J. Parsons, Research Fellow
Department of Fuel Technology and Chemical Engineering,
University of Sheffield, Sheffield, England

Abstract

Shock tunnels are normally operated with flow times of many milliseconds, as indicated by an approximately constant reservoir pressure. This testing time is at a maximum under conditions of contact surface tailoring. It is shown how considerable amounts of driver gas can penetrate far into the test gas and contaminate the latter much sooner than the arrival of the bulk of the driver gas. Under certain conditions, this process can drastically shorten the constant properties testing time, without materially affecting the pressure. High speed gas sampling results confirm this phenomenon in a shock tunnel, and indicate the arrival of large concentrations of driver gas in less than half the time indicated by pressure records. A possible mechanism for premature arrival of driver gas, by bifurcation of the reflected shock, is described.

Introduction

Shock tunnels have found a variety of uses, where a flow of gas at high temperature and pressure is required, and where short flow times can be tolerated. Many types of experiments can also be performed during the even shorter flow times available behind the incident shock or in the momentarily stagnant region behind the reflected shock in shock tubes.

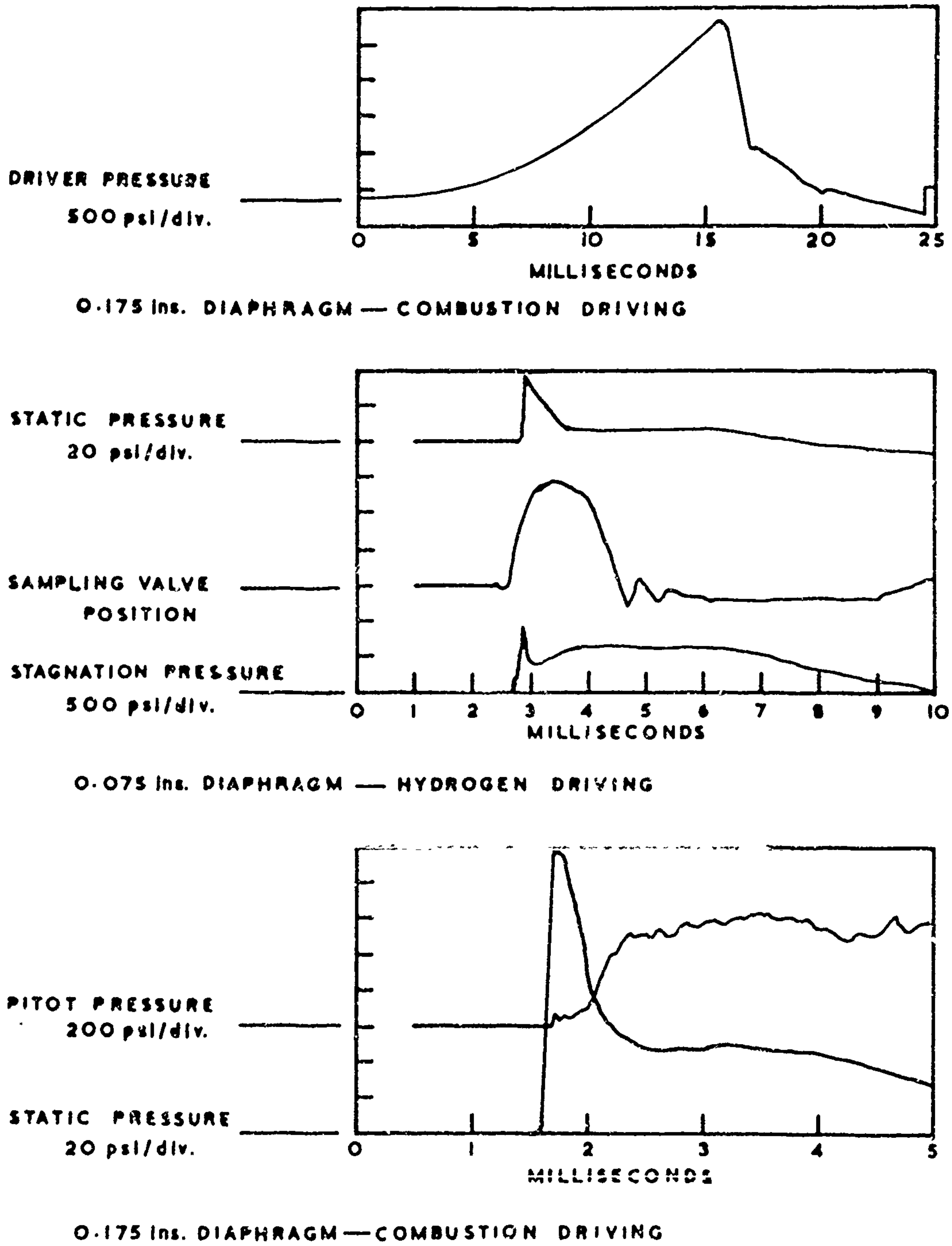
At least four different types of experiments can be listed here, for which shock tunnels or shock tubes have been widely used. These include the study of flows over aerodynamic shapes; gas dynamic flows, such as the study of nonequilibrium effects in nozzles; flows involving more complicated chemistry, such as combustion; and the production of hot gases as radiation sources for spectroscopic experiments. Of course, one could think of other applications or combinations of the above. Of the four mentioned, only the first is relatively insensitive to temperature, or to small changes in composition; one is usually interested in the Reynolds number and the Mach number.

Flow Time at Constant Pressure

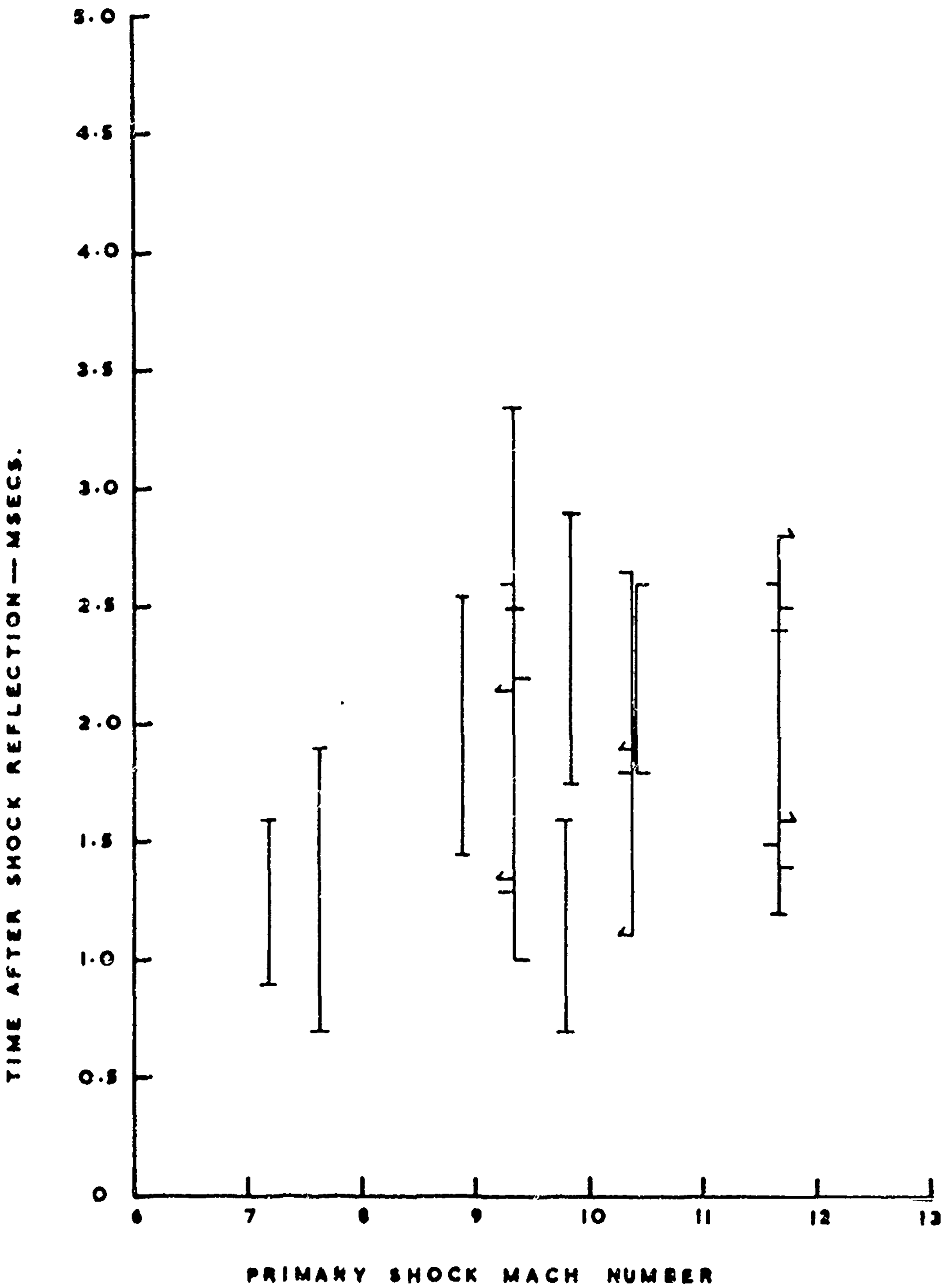
Since the starting process in a shock tunnel usually takes from 0.5 to 1.0 millisecond, it is obvious that we will require a useful flow time of at least one millisecond after shock reflection, preferably much longer. One limitation on the testing time at constant pressure is reflection of shock waves from the contact surface, which causes large disturbances in the pressure of the flow. This effect can be minimized by contact surface tailoring, so that the reflected shock

can pass through the contact surface relatively undisturbed. The testing time is ultimately ended by the arrival of the reflected rarefaction. The constant pressure testing time, neglecting the starting process, can be predicted, on a one-dimensional basis, as a function of the shock tunnel dimensions, the strength of the primary shock, and the nature of the test gas. This testing time, for a given shock tunnel, is found to be roughly inversely proportional to the speed of the primary shock. This imposes a small upper limit on the testing time if one must tailor at a high value of primary shock Mach number.

A comparative study of testing times was made on the shock tunnel of the Department of Fuel Technology and Chemical Engineering of the University of Sheffield. This shock tunnel was intended for combustion driving, but could also be driven with cold hydrogen. Reservoir conditions, with tailoring, were stagnation temperatures of about 6000°K and stagnation pressures of about 100 atmospheres. With combustion driving, the tailoring Mach number is about 9. A more complete description of the tunnel, pressure measurements, and gas sampling techniques will be found in Reference 1. A typical set of oscillograms of pressure and of sampling valve opening is shown in Figure 1. Examination of the trace of stagnation pressure will show that there is a considerable "plateau" of pressure after the initial starting transient. This plateau may have a duration of from 1 to 2 milliseconds, depending on the mode of driving, and agrees well with the theoretical predictions. A negligible extent of plateau results if one departs too far from the tailoring condition. Figure 2 shows a summary of pressure plateaus data, giving the extent in time of the pressure plateau, referred to the instant of shock reflection, as a function of primary shock Mach number.



1. Typical oscillograms from shock tunnel.



2. Pressure plateau vs. Mach number of primary shock.

Maximum duration of the pressure plateau should occur at or near the tailoring condition.

Premature Arrival of Driver Gas

Although it is apparent that the driver gas must eventually arrive at the end wall of the shock tube and flow through the nozzle, in a properly designed shock tunnel operated with contact surface tailoring, the contact surface should arrive after the reflected rarefaction and not influence the test gas. Experience has indicated, however, the possible premature arrival of some driver gas. Such contamination of even small amounts can have a very serious effect on many types of experiments, because of large fluctuations in composition and temperature (the driver gas is usually cooler than the test gas). It has been found that such contamination is not necessarily reduced by tailoring, and may reduce the constant properties testing time by a factor of two or more.

The author could find only a limited amount of information in the literature which gave unambiguous quantitative data regarding driver gas contamination during the constant pressure period of flow. The pressure data referred to above, as is typical of such data, will give no clue as to driver gas arrival. However, thin film transducers[2,3], either on the end wall of a shock tube, or on a flat plate in the test section of a shock tunnel, indicated large fluctuations in heat transfer under certain conditions during periods of relatively constant pressure. These results were interpreted to mean premature arrival of quantities of driver gas. Parsons[4], in an MHD experiment, noted that abrupt disappearance of electrical conductivity during the constant pressure period, a situation

consistent with sudden mixing of cold driver gas. Edwards[5], placed trace amounts of CO_2 in the driver, and was able to detect premature arrival of the driver gas by infra-red absorption in the CO_2. More quantitative measurements of the early arrival of driver gas have been accomplished by high speed gas sampling in test sections of shock tunnels. One of the earliest reports of this technique is from the Cornell Aeronautical Laboratories[6], where a fast mechanical valve permitted sampling period of about 2 milliseconds. Driver gas (helium) was found to arrive in much less time than that indicated by constant pressure. More recent sampling at the University of Sheffield will be described in the next section. In the latter, the constant pressure testing time was much shorter, due to the higher Mach numbers of the primary shock.

High Speed Gas Sampling Results

Sampling measurements reported here were done in the Hypersonic Shock Tunnel of the Department of Fuel Technology and Chemical Engineering of the University of Sheffield, already referred to. The constant pressure periods, as already noted in Figures 1 and 2 were 1-2 milliseconds, in good agreement with theory.

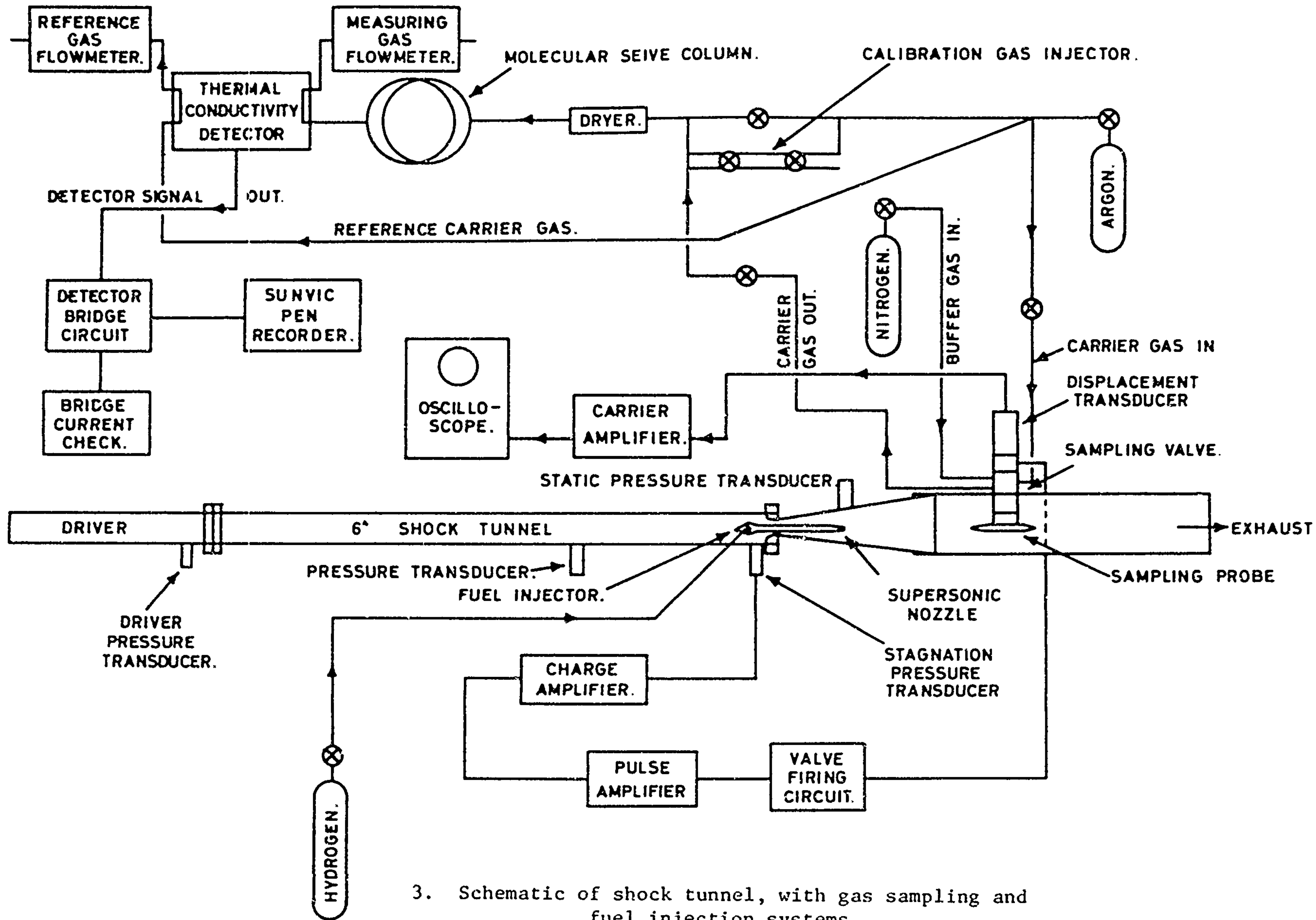
A sampling probe was attached to a high speed sampling valve and located at the exit of a nozzle with an area ratio of 4, which would expand the flow to about $M = 2.7$. The nozzle was equipped with a fuel injector so that experiments with supersonic combustion could be performed in the test section.

The rapid sampling valve, solenoid operated, was obtained

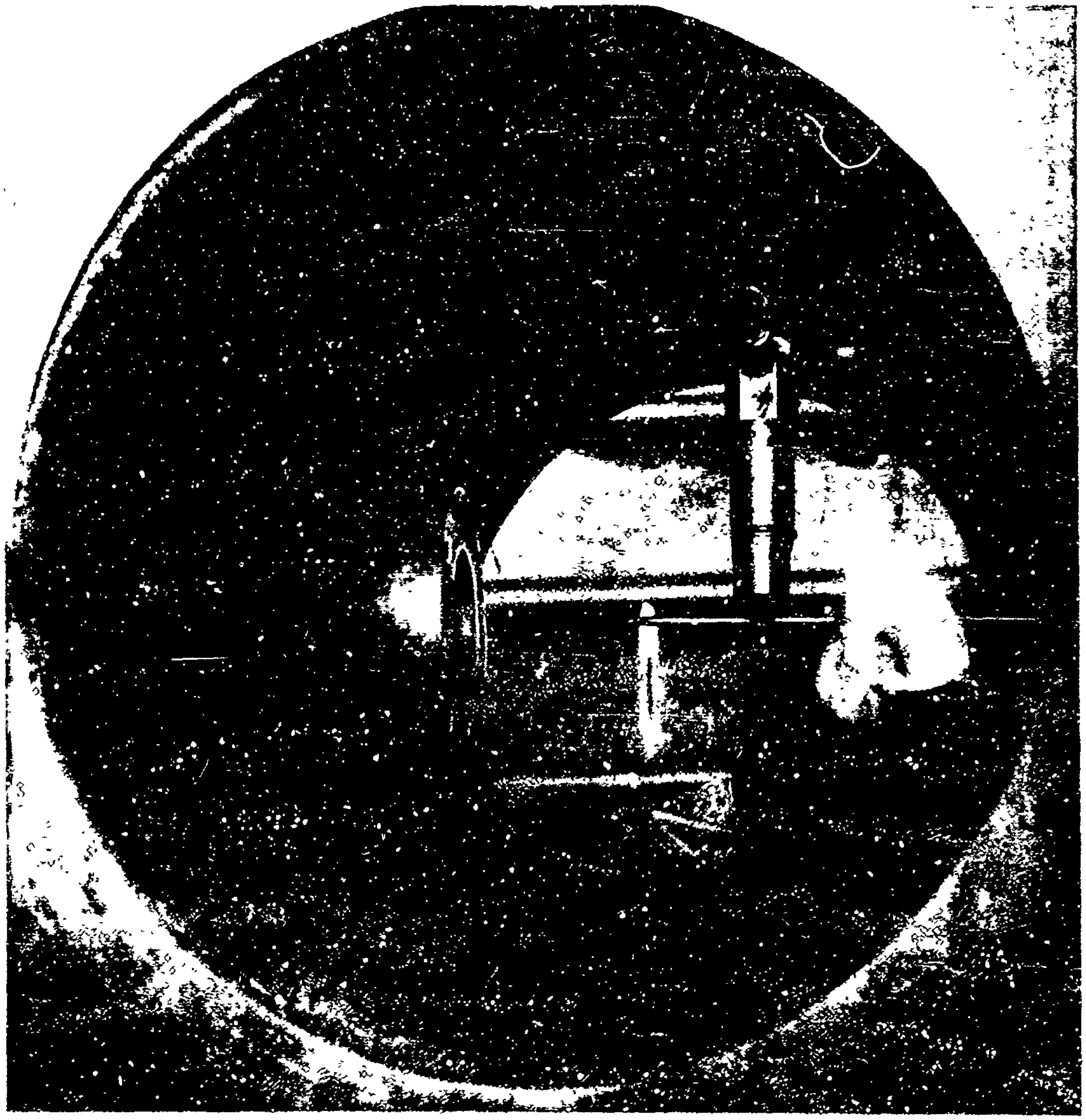
from the British Petroleum Research Center, Sunbury-on-Thames. Typical opening times for the valve was 1.5 milliseconds, and it could be operated at any chosen point in time with respect to the start of the flow in the nozzle. A small sample of gas was extracted from the flow and injected into a carrier gas stream, which then carried it to a gas chromatograph for analysis. Driver gas could readily be separated from test gas. A schematic drawing of the shock tunnel, with gas sampling and fuel injection systems, are shown in Figure 3. A photograph of the sampling probe and valve, located in the shock tunnel test section, is shown in Figure 4.

Sampling results indicated early arrival of driver gas, soon after the starting shock. A summary of the driver gas contamination results is shown in Figure 5, where concentrations of helium or hydrogen (relative to nitrogen in the sample) are plotted against time after shock reflection. The horizontal bars indicate the time of opening of the sampling valve. With the amount of data available, it is not possible to determine the exact time of arrival of the driver gas, because of the finite sampling interval. The dotted line indicates the latest possible arrival of driver gas, based on the data. Variations in primary shock Mach numbers, as indicated, are not considered significant, as there was no consistent effect on the testing time over the Mach number variation reported.

Anomalous fluctuations in end wall heat transfer within 200 microseconds after shock reflection were reported in Reference 3, but a direct comparison with the present results is not possible, because conditions were considerably different. Gas sampling results in Reference



3. Schematic of shock tunnel, with gas sampling and fuel injection systems



4. Photograph of sampling probe and valve in shock tunnel test section

2 resolved discrepancies in heat transfer records, said to be due to intrusion of driver gas in the test gas. At primary shock Mach numbers greater than 5, considerable concentrations of helium were detected 1-2 milliseconds after the flow started.

Mechanisms for Premature Arrival of Driver Gas

At least two models have been proposed which can provide mechanisms for premature arrival of driver gas. One is that of contact surface instability, in which the interface between driver gas and driven gas may become turbulent, and considerable amounts of driver gas may penetrate into the driven gas as the interface travels down the tube. Such instability may be induced by erratic diaphragm bursting, development of turbulent flow behind the shock, or of combustion at the interface. Copper[6] reported instabilities in the pressure history in a shock tunnel in which hydrogen was driven into air, while such instabilities were much reduced, and the testing time longer when nitrogen was used as the driven gas instead of air. These instabilities he attributed to combustion of hydrogen at the interface. In the University of Sheffield shock tunnel, we also observed smoother pressure records when hydrogen was driven into nitrogen instead of air, but the former gas is unsuitable for combustion experiments. Since a certain amount of interface instability is always present, a critical degree of instability is difficult to define. It appears that excessive interface mixing due to instability is not a unique function of primary shock Mach number.

A second possible mechanism for early contamination by driver gas, that of bifurcation of the reflected shock, is more easily defined,

and is dependent on the primary shock Mach number. Summaries of recent work on this phenomenon have been written by Davies[3,7] at the National Physical Laboratories at Teddington, England. Under certain conditions in the shock tube, the reflected shock bifurcates as it passes back up the tube through the gas which has been set into motion by the incident shock. A simple theory has been devised, which predicts that bifurcation occurs when the total pressure of the gas in the boundary layer (assumed constant) is less than the static pressure of the gas in the free stream after it has passed through the normal portion of the reflected shock. The bifurcation provides a mechanism for the low energy gas in the edge of the boundary layer to negotiate the passage of the reflected shock, so that it will appear afterwards as the same pressure as the gas at the center. This shock-boundary layer interaction causes separation of the latter, and a turning of some of the flow, as indicated schematically in Figure 5, taken from Davies' work. In this figure, the shock is assumed fixed, with the gas and walls assumed moving as shown. Compression and expansion waves are also shown.

When this bifurcated reflected shock meets the contact surface, that portion of the latter which passes through the foot of the shock is deccelerated less than that which passes through the normal portion of the shock. The driver gas passing through the foot of the bifurcated shock, now being at a higher velocity than the remainder, will reach the end wall much sooner, will then flow radially inward, and out through the nozzle much sooner. Pitot pressure measurements near the wall under these conditions have roughly verified the model. Schlieren photographs of the bifurcated reflected shock have even verified the

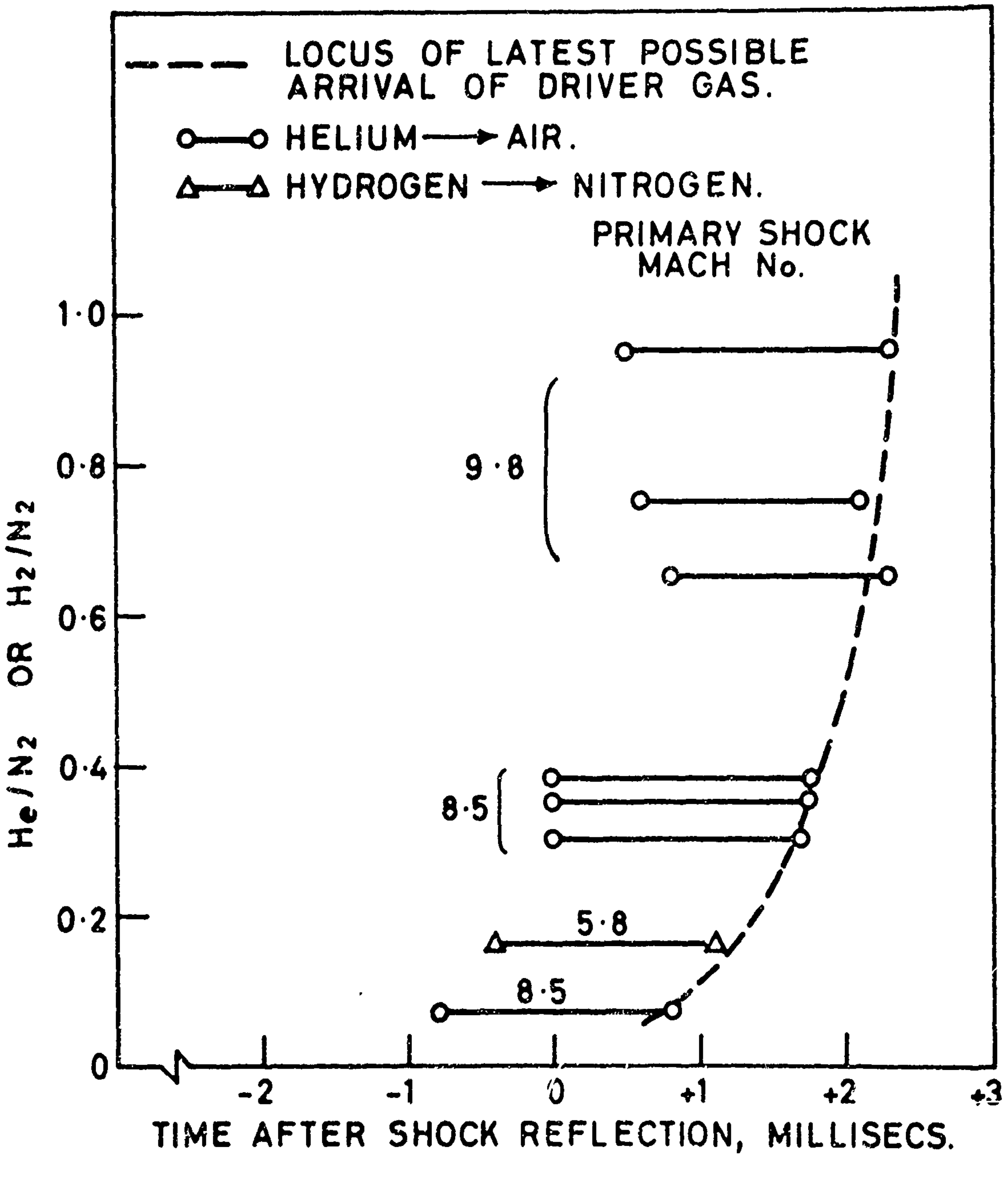
oblique shock angles predicted by the theory.

Davies also reported measurements made with an array of thin film gages placed stratigically over the end wall of a shock tube. These thin film gages verified that the flow of cold gas was radially inward, and occured in time much sooner than did the bulk of cold driver gas passing through the middle of the reflected shock. The time of arrival was also consistent with velocities calculated for gases passing through the foot of a bifurcated shock.

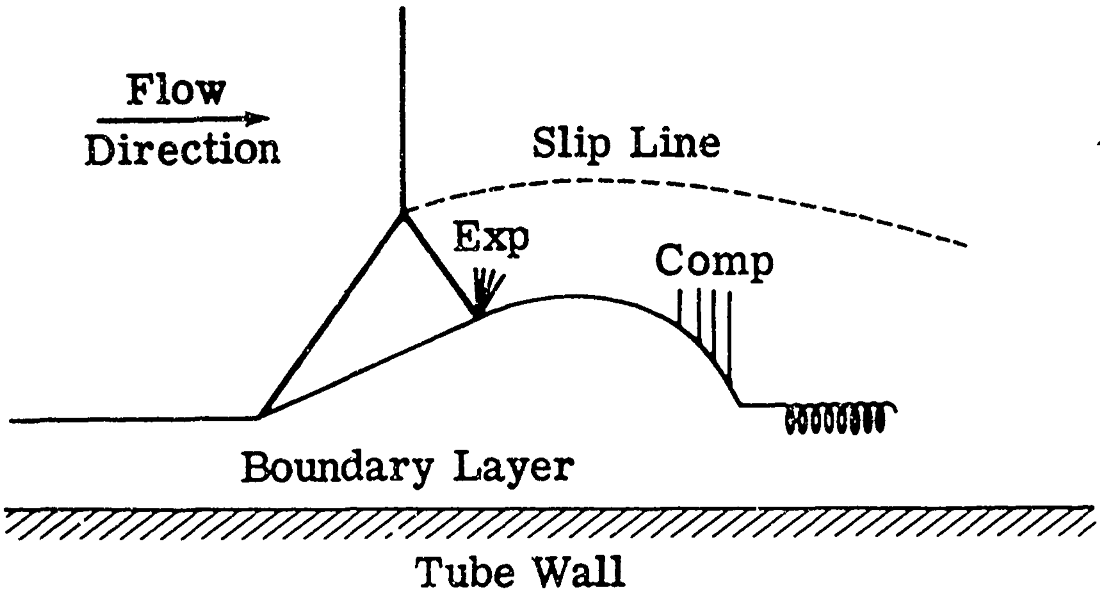
The theory also predicts that this bifurcation, for diatomic gases, is significant for incident shock Mach numbers between 3 and 16. The range for monatomic gases, such as argon, is much narrower. These predicted trends have also been verified roughly by experiment. This dependence on Mach number provides an approximate means of distinguishing between the contact surface instability model and the shock bifurcation model, since the former has no clear dependence on the Mach number of the incident shock, although it is also apparent that both may occur under a wide range of conditions. Edwards[5], using CO_2 tracer techniques, concluded, with the above reasoning, that the shock bifurcation mechanism was probably predominant in producing early driver gas contamination in his experiments.

Conclusions

It has been shown, by both theory and experiment, that mechanisms exist for the early arrival of driver gas into the test gas of shock tubes or shock tunnels. This effect can be expected to be especially pronounced at incident shock Mach numbers greater than 3. It has been



5. Driver gas contamination in a shock tunnel



6. Schematic diagram of reflected shock bifurcation model

shown that pressure records give no indication of this contamination, and that the constant properties testing time may be less than the constant pressure testing time by a factor of two or more. Gas sampling has proven to be a rather quantitative measurement of the early arrival of driver gas, an important consideration in evaluating shock tubes or shock tunnels for chemical measurements.

References

1. Richmond, J. K., and Parsons, R. J., "Application of Rapid Sampling Techniques to Supersonic Flows of Gas Mixtures in a Shock Tunnel", Report H.I.C. 118, Department of Fuel Technology and Chemical Engineering, University of Sheffield, Sheffield, England, September 1968.

2. Martin, James F., "Investigation of Test Time at Under-Tailored Conditions in a Shock Tunnel", Cornell Aeronautical Laboratory, Inc., Buffalo 21, New York, Report No. WTH-026, May 1963.

3. Davies, L., "The Interaction of the Reflected Shock with the Boundary Layer in a Shock Tunnel", 1966, AD 805 503.

4. Parsons, R. J., Ph.D. Thesis, Department of Fuel Technology and Chemical Engineering, University of Sheffield, 1969.

5. Edwards, D. H., "Infra-red Studies in a Shock Tube", 18th Shock Tube Liasion Meeting, Imperial College of Science and Technology, London, April 25, 1968.

6. Copper, John A., "Effects of Interface Combustion and Mixing on Shock Tunnel Conditions", AIAA Journal, Vol. 2, No. 9, September 1964, pp. 1669-1671.

7. Davies, L., and Wilson, J. L., "The Influence of Shock and Boundary Layer Interaction on Shock Tube Flows", N.P.L. Report 1228, A.R.C. 29 064, Hyp. 615, 4th May 1967.